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I) INTRODUCTION : AIMS OF THE DELIVERABLE

Water is the main constraint of crop production in the Sudano-sahelian area of West Africa. The pre-dominant food crops in this environment are millet and sorghum, both C4-type cereals. Maize is cropped only in the southern Sudanian area.

Millet and sorghum are the traditional crops. They are commonly sown at different dates, depending on farmer strategies and of their perception of the monsoon onset (Vaksmann et al., 1996; Sivakumar, 1988). The traditional varieties, which are the main cropped ones, are generally photoperiod sensitive: this allows them to reach maturity at the same fixed date every year. Lengths of cycles are variable according to sowing date. On the other hand the modern “improved” varieties are generally non-photoperiod sensitive, reaching their maturity at different dates according to sowing date and temperature conditions (Bacci and Reyniers, 1998). Crops could be affected by drought at different periods of their cycle, and since sensitivities stages to drought are different, consequences on yields could differ strongly.

The main processes governing crops functioning are quite well known, and have been modelled in different ways. The operational problem, however, is how to translate the scientific knowledge into confident information about crop failure risk, in order to allow extension staff to give relevant advice, and policy makers to decide operations allowing food security.

Since the devastating droughts of the 1970s, this challenge has been addressed, on one hand by continuous crop yield monitoring (e.g., DIAPER project, Maraun et al., 1994), and on the other hand by new regional processes for climatic data acquisition and pooling, feeding a seasonal yield forecasting tool (DHC system) managed by Agrhymet (for the 9 CILSS member countries).

This requires simple and robust tools relating climate to agronomic impact.

In West Africa, two generic tools have been mainly used by extension services : the FAO Cropwat model (Doorenboos and Pruitt, 1977; Doorenbos and Kassam, 1979) and SARRA (Système d’Analyse Régional des Risques Agro-climatiques; Baron et al., 1999) developed by CIRAD and its West African partners. Several version of SARRA are used under different names.

In 2000, collaborative efforts were initiated by Cirad, Agrhymet and several European partners within the PROMISE project (<http://ugamp.nerc.ac.uk/promise>) first and then within the AMMA project (<http://amma.mediasfrance.org/index>), to develop a new tool allowing to assess the impacts of climate on agriculture, aiming at the assessment of the impacts of climate change and variability. Specifically designed for West African cereals, a complete crop model was developed, called SARRAH. SARRAH simulates water and radiation balances, and biomass production and partitioning that take into account sowing density and photoperiod.

Considering the objectives of the AMMA project, a specific operational tools is required, which should be adapted to different kinds of study:

- studies about impacts of climate change and variability on agriculture and food security;

- seasonal and on time intra-seasonal crop yield forecasting;
- targeted plant environment (TPE) studies: identification of varieties or crop features adapted to specific climatic environment;
- validation of crop modelling concepts.

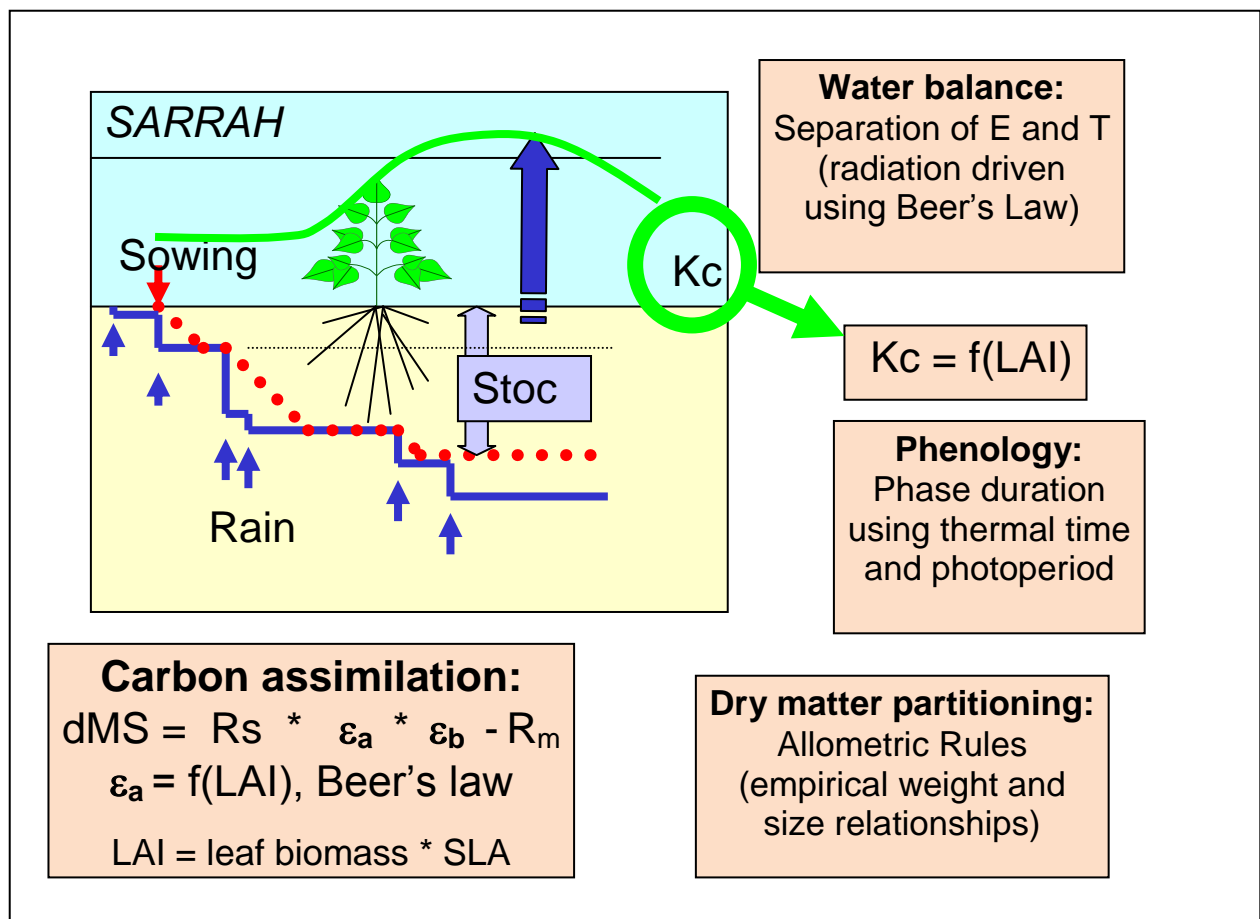
To reach those objectives, two kinds of actions have been developed:

- Adaptation and validation of SARRAH crop model in order to improve biomass and yield assessment: i) new concepts integration; ii) comparison of the different SARRAH existing versions in order to choose the adequate algorithms. A new standard version well adapted to regional agroclimatic studies has been elaborated. Different sets of results coming from experiments or farmers fields have been compared with simulations.
- Improvement of the « user interface » in order to give users much more flexibility, allowing them: i) to easily create and manage multiple simulations scenarios oriented towards different objectives ; ii) to make easier and semi-automatic data transfer between users (with possibility to introduce new variables) ; iii) to make easier the analysis of simulation results through the possibility to define some automatic processes.

II) THE CROP MODEL SARRAH

II.1) Antecedents

SARRAH (Dingkuhn 2003) is a crop model recently developed on the basis of SARRA, the water balance model frequently used by agronomists and agro-meteorologists working in the Sahel (zoning and risk analyses: Affholder 1997; Baron et al. 1999. Yield forecasting: Samba 1998). SARRAH based models typically simulate attainable yields deterministically at the field scale, but may also be stochastic and operate at variable temporal and spatial scales. Extrapolation from plot to region is routinely done by Agrhymet (Niamey) for agro-meteorological forecasting using the DHC system (Cirad and Agrhymet project), which includes SARRA as a component (Samba 1998; Samba et al. 2001). SARRAH was structured to enable such applications as well, but with greater physiological detail.



Only details relevant to the version of SARRAH used here are described here.

Soil water dynamics. The model simulates at daily increments water runoff and infiltration using an empirical threshold of 20 mm (Baron et al. 1996). The soil is divided into a 20 cm top layer used to simulate evaporation and a layer of variable thickness representing the wetted zone. Water holding capacity of the soil between wilting point (pF 4.2) and field capacity of the soil is calibrated from available soil data, and was set to 100 mm m⁻¹ for this study to represent a sandy soil. The root front, which descends at empirical rates depending on the growth stage, follows the wetting front but is also limited by it. Water extraction from the soil consists of two additive components, surface evaporation and extraction from the root zone through transpiration. Fraction ground cover is used to partition evaporative demand acting on the soil and the plant. Ground cover is computed from simulated leaf area index (LAI) and an extinction coefficient K_{df} according to Beer's law.

Plant water use and drought simulation. Drought level is evaluated from Fraction of Transpirable Soil Water (FTSW) calculated for the bulk root zone, which is the relative degree of soil saturation between wilting point and field capacity. This variable acts via feedback on plant transpiration using FAO guidelines (P-factor system; Allen et al., 1998) and on carbon assimilation as a reducing factor. Maximum evapotranspiration of the soil and canopy is determined by using a crop factor K_c with potential evapotranspiration (PET) according to FAO guidelines for different crop species (Doorenbos and Pruitt 1977; Doorenbos and Kassam 1979).

Carbon assimilation and partitioning. Potential assimilation rates are calculated from ground cover, solar radiation and radiation use efficiency (RUE; Sinclair and Muchow 1999) before applying the drought related reduction. After subtraction of a temperature and biomass dependent maintenance respiration term (Penning de Vries 1989), biomass is partitioned

during vegetative stage between root, stem and leaves according to empirical, allometric rules (Samba et al. 2001). Grain filling, however, is simulated with somewhat more detail to allow for variable harvest index, by determining sink capacity during pre-floral stages and inducing leaf senescence after flowering when sink capacity exceeds current assimilation rate. Leaf biomass is converted to leaf area using Specific Leaf Area (SLA; Penning de Vries et al. 1989) whose dynamics are simulated on the basis of a genetic minimum and maximum value.

Phenology. . The model is capable of simulating variable crop duration depending on thermal time and photoperiodism.. Thermal time was simulated by assuming a base temperature of 10° C.

Rainfall dependent sowing dates. Sowing date is optionally generated by the model using a threshold function approximating farmer's criteria. It is determined by a rain event followed by a period of 20 days during which crop establishment is monitored. The crop is considered failed, triggering automatic re-sowing, if during 10 out of 20 days water-limited transpiration is equal or below 30% the crop's potential transpiration. These rules, extracted from regional survey studies, are adapted from Agrhymet's DHC yield forecasting system (Samba 1998) for the CILSS member countries which are Burkina Faso, Cape-Verde, Gambia, Guinea Bissau, Mali, Mauritania, Niger, Senegal, Chad (Permanent Interstates Committee for Drought Control in the Sahel ; <http://www.cilssnet.org/>).

II.2) Evolutions

In the last few years, different researches in West Africa, developed within and outside of AMMA allowed to improve SARRAH model. According to the focuses of those researches different versions of SARRAH were developed. It appeared necessary to compare and combine those different versions in order to develop a new standard one well adapted to the objectives of the present deliverable. Capability to assess regional yields increased.

Comparisons between observed and simulated data were used to sustain this process (see Chapter 4 : Assessment).

It doesn't appear relevant to present here all the modifications that were incorporated to the new SARRAH version.

We will just briefly present a major one, dealing with the modelling of the crop photoperiod sensitivity. A new agronomical concept was developed, and has been recently published. Adaptation to variable climate in West African dryland cereals, namely sorghum and millet, is in large part a function of temporal escape from stress periods through adapted phenology. These escape mechanisms, which are highly genotype and environment specific, need to be integrated into a broader modelling framework of plant drought responses and yield potential.

A detailed study was conducted on sorghum phenology, including photoperiod response. This gave rise to a new, innovative model called Impatience. Through the simulation of variable (aging dependent) day length thresholds, this model is able to explain and predict the phenological behaviour of a large spectrum of traditional and improved sorghum genotypes. The model itself and its validation were published in European Journal of Agronomy (Dingkuhn et al., 2007). It was then incorporated into the general crop model SARRAH, for which versions calibrated for millet, sorghum, maize and upland rice are now available for applications by AMMA teams.

II.3) Data required

Plant & soil:

Set of variables are calibrated for a list of varieties and soils :

- to simulate the crop's carbon budget that determines biomass build-up and phenology
- to simulate the water balance taking into account total and readily available soil water and runoff features.

Data required:

- crop variety
- sowing date
- type of soil and depth
- cultural practices : sowing date, sowing density, irrigations

Climate Data:

Simulations require daily values of rainfall and standard meteorological data :

- global radiation (Rg) or insolation (Ins);
- temperature (maximum and minimum: Tmax and Tmin);
- wind speed (at 2 m; Ws);
- humidity (maximum and minimum: Hmax and Hmin);

The model computes the potential evapotranspiration (PET).

Temperatures and global radiation govern crop growth.

III) SIMULATION TOOL : THE ECOTROP PLATFORM

III.1) Antecedent

The original Ecotrop platform was developed to allow users develop, test and manage new concepts and modules of crop models for annual and perennial crops. This platform allowed develop crop models based on a library of modules that can be selected, run them, and then evaluate them with the help of tools such as sensitivity analysis and parameter optimisation, database management and graphic interface.

This original platform was mainly used for Oil palms and Millet growth simulation.

III.2) Evolutions

To be in the position to better answer AMMA objectives, the platform was completely modified and improved. Computer science students participated to those deep evolutions (Adèle Sauguet, 2005 ; and Antoine Pastor, 2006, from Université Montpellier II IUP Génie Mathématiques et Informatique).

The main evolutions are the following: 1) setting new tools and defining a new way to define simulations, allowing to easily define multiple simulation scenarios; 2) setting new tools and new data organisation, allowing users to easily exchange all kind of data and even simulation scenarios; 3) setting new tools to make easier the management and the analysis of important numbers of results (historical and spatial analysis, with data coming from many sites). To

reach those objectives the data base and data management system of the software were totally modified.

Multiple Scenarios

Two tools have been developed to assist the user in the definition of multiple scenarios using the data that are available in the database:

- set of different soils ;
- technical intervention (sowing date, sowing density, irrigations) ;
- set of varieties, with different features ; and those features can be modified also ;
- climatic data, with the possibility to combine rainfall data of one local site with the meteorological data of a different, but nearby site ;

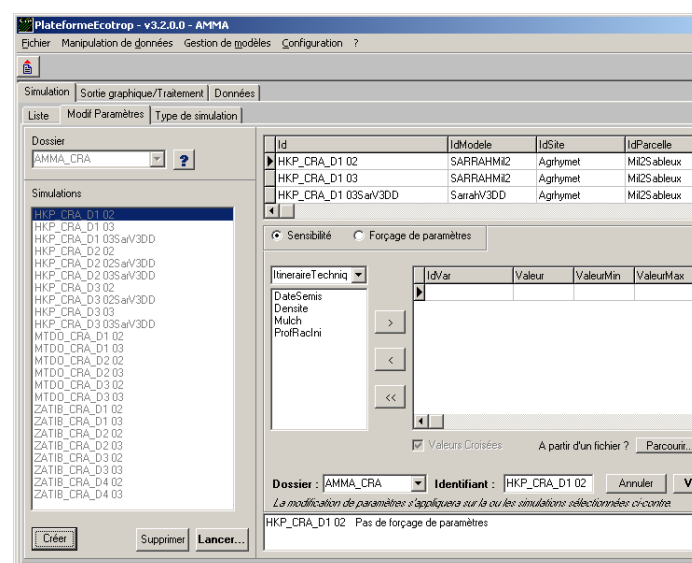
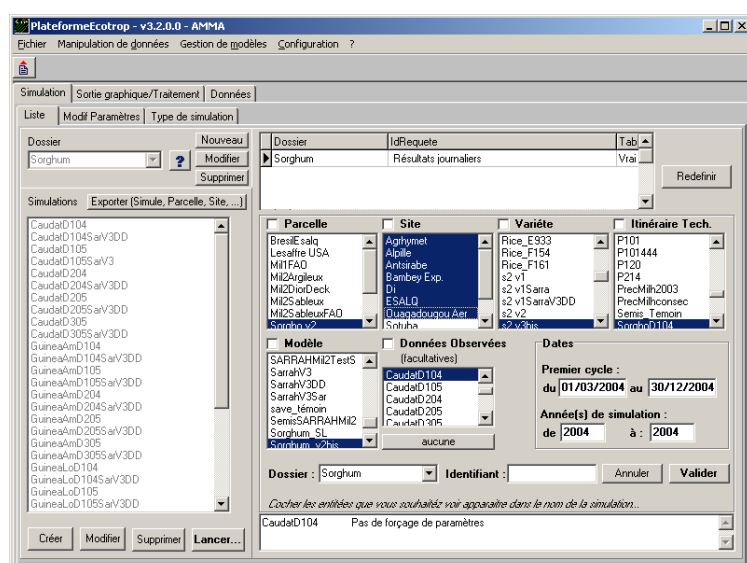
The first tool allows to very easily define a simulation or a set of simulations, even many, by an easy selection process of the different components of the simulations, i.e. the varieties, the climatic data, the soil type, and the technical practices. Simulations considering all the desired combinations of situations are automatically defined.

Some of the main applications are the following:

- possibility to assess the potential of different varieties (ecotypes) in many climatological situation under one or several agronomical managements.
- climatic scenarios could be used instead of historical observed meteorological data, allowing to assess climate change and variability impacts on crops according to different varieties and/or agronomical managements.
- diversity of soils and runoff features can be considered.

Those examples are not exhaustive.

A second tool allows sensibility analysis, for instance considering varieties or soils features. Also, according to the scale of the study, the impacts of the uncertainties on the data could be assessed too. To do that the user defines simulations using different values for one parameter or a set of parameters, exploring the probable uncertainties.



Exchange data

The exchange data tool was developed in order to allow the users to exchange all kinds of data and information, and even simulations scenarios. When it is necessary, the tool automatically updates the data base, incorporating without any problem new parameters or variables (new fields in the data base).

The files containing the data and information that the users want to exchange are text files that are easily created by the users. Exportation, importation and then data base update are automatic. Those text files could also be modified or created by other software such as Excel or Word.

The two described tools recently developed for the Ecotrop platform make much more easier all the most frequently performed applications: researchers need to develop and test new modelling concepts, and then need to play with new variables or parameters. The tool developed allows easily to do that and to automatically actualise the data base.

Results management and analysis

Defining multiple scenarios implies that simulation results can be handled differently. Namely, values of a given variable should be available at various time steps, calendar based or relatively to crop phenology or thermal time intervals. Aggregated results (sum, average, etc...) are then stored in a text file (or database table) in order to optimise data storage and analysis. Different types of queries can be defined in a list and added to simulation scenarios. For example, for a climate change scenario, one might want to have for all sites and all years, only biomass yields at the end of the crop cycle. One may also want to have some indicator of plant status every month or at every interval of 100 degree days.

IV ASSESSMENT

The quality of the model was assessed through comparisons between simulated and observed data coming from agronomical experiments and farmers fields.

IV.1) Agronomical experiments:

Detailed experimental and modelling studies were conducted on millet and sorghum in order to develop tools to predict varietal fit to different climatic contexts. This is of great importance for the accurate evaluation of the impact of climate change scenarios on crops, because any such study must take into account adaptive measures taken spontaneously by farmers (tactical adjustments: choice of cultivar and cropping calendar).

Up to now the data that were used came from different agronomical experiments developed within different projects, but not within AMMA. The main sets of data came from (i) Agrhymet experiments on Millet developed within the PhD work of M. Alhassane Agali; (ii) IER-CIRAD experiments on Sorghum developed within the PhD work of M. Mamoutou Kouressy.

Experiment on Millet:

Based on experimental work in Niger in 2002-2003, the SARRAH crop model was calibrated for three varieties types of millet, representing the most used by farmers in Niger. Varieties HKP, ZATIB and MTDO were sown in two different trials, one with two different sowing dates, and the other with two levels of nitrogen fertilization. Regular phenological observations and biomass sampling (leaves, stems, grains) were conducted on both trials and an automatic weather station was installed nearby the experimental plots to collect data on temperature, rainfall, solar radiation and wind speed.

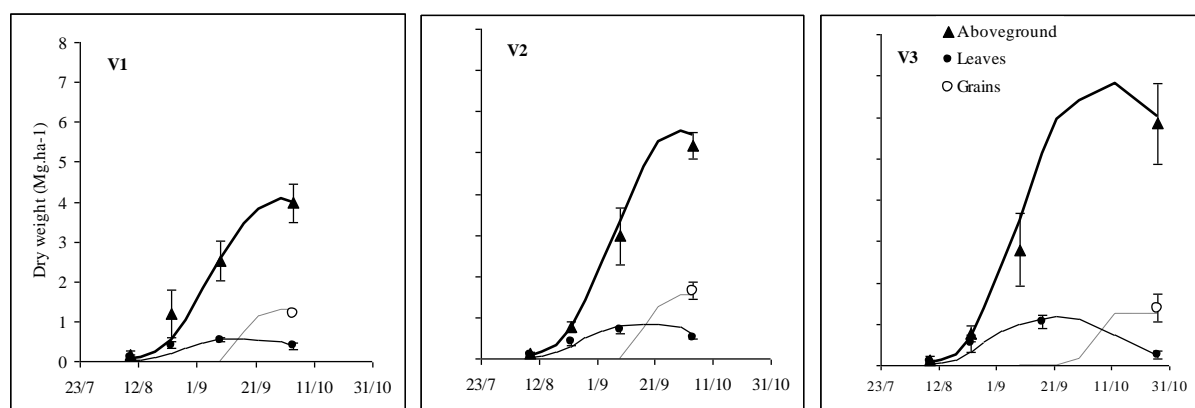


Fig. 1. Observed (points) and simulated (lines) biomass yields of three millet varieties in Niger. AGRHYMET 2002. V1= HKP, V2=ZATIB, V3=MTDO.

Experiment on Sorghum:

Based on experimental work in Mali in 2004-2005 (Kouressy et al., 2007a), the SARRAH crop model (in its version that includes the new phenological sub-model Impatience (Dingkuhn et al., 2007) was improved, calibrated and validated for different sorghum varieties.

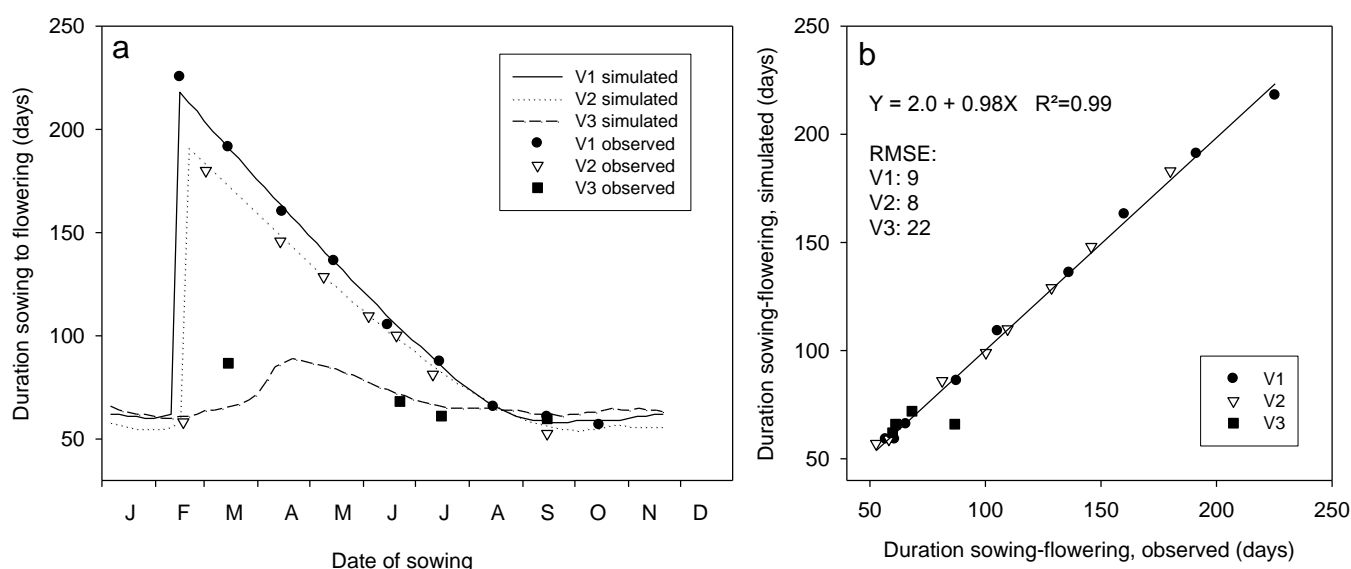


Fig. 2. a) Observed (points) and simulated (lines) duration from sowing to flowering of three contrasting sorghum genotypes (V1-V3) as a function of sowing date at Bamako; b) Relationship between observed and simulated duration.

IV.2) Farmers fields

If crop models are to be used to translate climatic scenarios into crop yields on farmers' fields, it is necessary to know (1) the range of variability of actual crop yields in current production systems, and (2) the fraction of this variability that can be attributed directly to the climatic variables provided by climate scenarios (e.g., rainfall, temperature, air humidity and solar radiation). Multi-annual field surveys were thus conducted in the $1^{\circ} \times 1^{\circ}$ observatory near Niamey (similar to GCM pixel) to relate plot level millet yields and production parameters to local rainfall and climate parameters. The SARRAH model was then used to explain the components of yield variability that can be attributed to these parameters, as well as to crop variety, sowing date and other factors.

Results indicate that yields vary strongly within village communities and among them. About 65% of variability among villages could be explained by the model and was thus due to local rainfall and climate variability, namely rainfall amount and distribution within the season (Fig 3). Most of the explanatory power of the model was lost, however, if regional rainfall records was used (Baron C. & al., 2005), or defined from the nearest synoptic station, instead of village level records. This was due to extreme variability of rainfall within the $1^{\circ} \times 1^{\circ}$ observatory.

Consequently, about 65% of yield variation is due to climatic factors and thus, directly sensitive to climate variability and change within the ranges observed. But to capture these in terms of local agricultural impact, it would be insufficient to have data from synoptic stations only, because they are not representative for any larger land entity. Impact prediction of climate variability on local millet yields must thus be derived from climate, namely rainfall, data that captures both the small scale variability within GCM pixels (to ensure accurate local simulations) and aggregate weather patterns within a pixel (to ensure representativity). A publication on this is in preparation

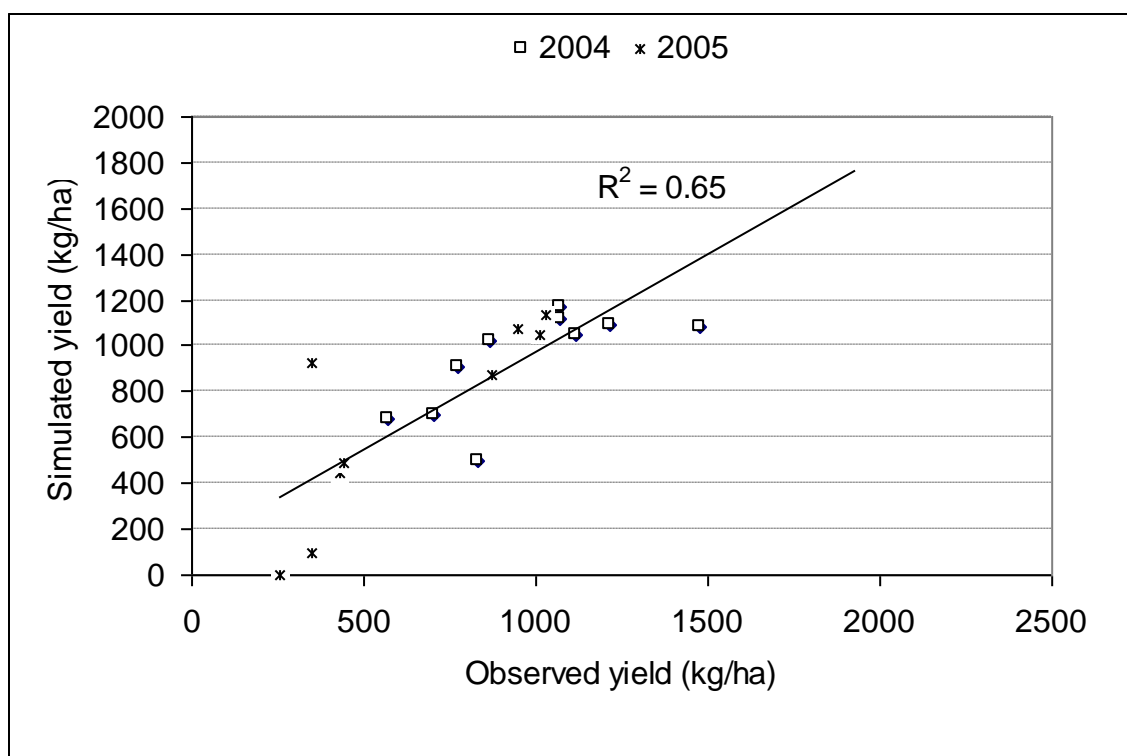


Fig. 3. Relationship between observed and simulated millet yields in 2004 and 2005 in 10 villages in the squared degree area around Niamey, Niger.

This type of study is currently being reproduced in Mali and Senegal, and for three cereal crops (millet, sorghum and maize) to constitute a regional database that will enable accurate scaling down of climate/weather scenarios to local scale.

V) PERSPECTIVES

The extension of AMMA to African partners gives us the opportunity to amplify our research approach and assess the accuracy of the crop model in different agro-ecological zones in West Africa.

Developed within different projects, a series of studies with the platform was applied under climate constraint (Brazil, Burkina Faso, Mali, Niger...). The resulting, modelling based methodology can be generalized for applications to scenarios of climate change and variability.

Evaluate the crop model in different agro-ecological sites in West Africa

It is important to stress that other sets of agronomical experiments started recently are in order to be in the position to validate SARRAH for the majority of West African cereal varieties; within the extension of AMMA project (AMMA-TTC, 2007-2009) in Senegal, Mali, Niger

and Burkina Faso on different local varieties of millet, sorghum and maize. Another set of experiments was carried out by CERAAS-ISRA and CIRAD in Senegal focusing on sowing density impacts on crop radiation balance and growth, in order to improve some modelling concepts. With the extension to new partners, we are now able to conduct 1) on-farm crop monitoring at various contrasted sites and 2) better characterize local varieties through experimental trials. This is being done in 4 countries (Burkina Faso, Mali, Niger et Sénégal) at locations contrasting in climate and agricultural practices in order to be able to estimate on-farm yields from plot to village and regional scales.

Assess a modelling based methodology

The SARRAH crop model (in its version that includes the new phenological sub-model) was applied to historical climate records (1972-2005) along the N-S climatic gradient in Mali, covering sites/latitudes having 400-1200 mm of annual rainfall. The resulting study (Kouressy et al., 2007b) gives precise indicators of varietal fit, ranges of feasible sowing dates and indicators of risk of biotic and abiotic stresses for the gradient (Fig 3). This study is based on a multi-criteria simulation of agro-ecological fit of three contrasting sorghum genotypes (V1-V3) at three locations in Mali (Nara, Sahel; Bamako, Sudan savannah; Sikasso, Guinea savannah). Five sowing dates were tested on 34 years of historical weather records. Applying the additional criterion that sowing should be done early in the season to avoid soil nitrogen losses, the following pattern emerges: V1 is adapted to Bamako (sowing in June) and Sikasso (May); V2 is mainly adapted to Bamako (sowing in June); and V3 is only adapted to Nara (sowing in July). Photoperiod sensitive V1 provides the greatest flexibility of sowing dates within its zones of adaptation.

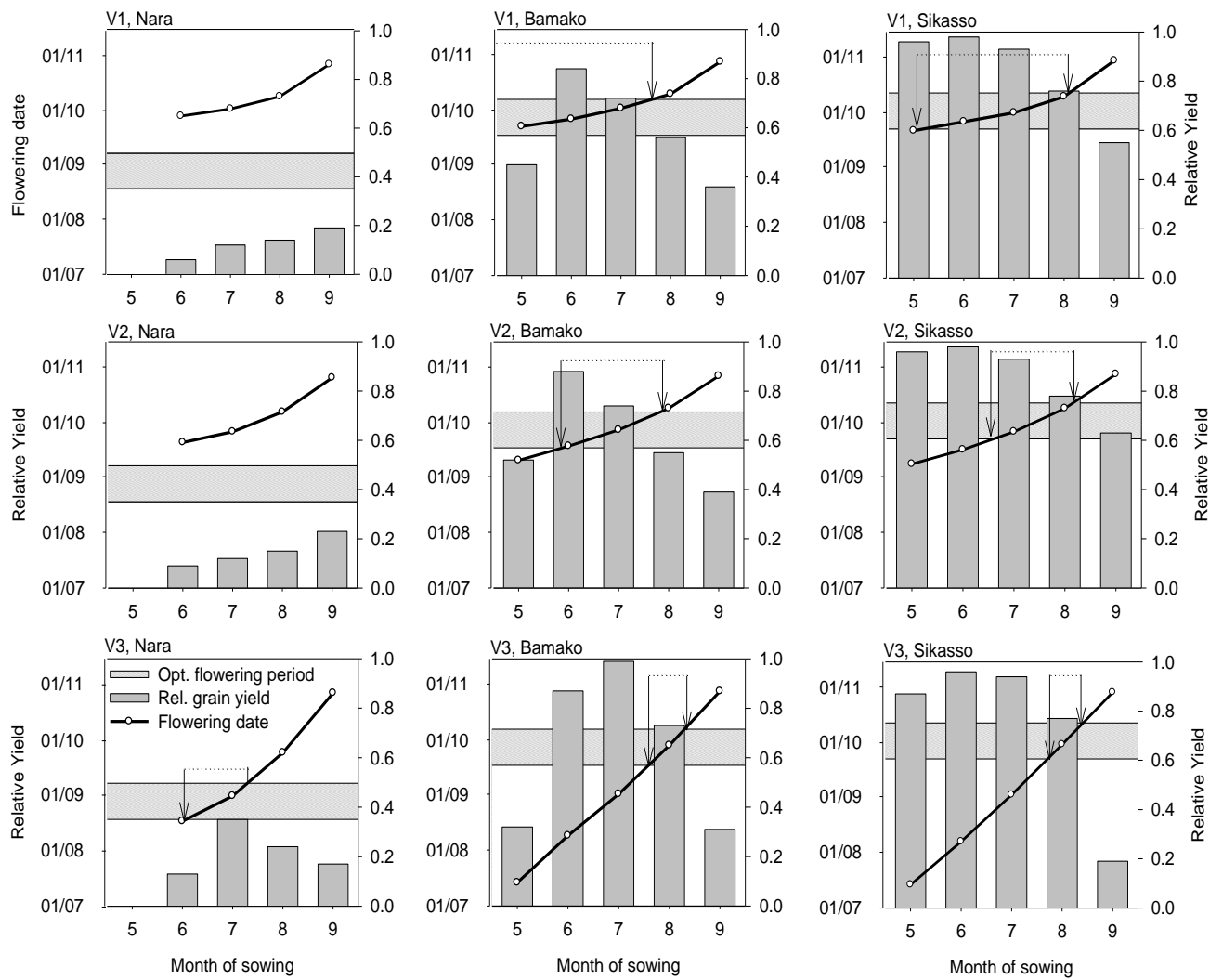


Fig. 4: Grey columns: mean relative grain yield (water limited / unlimited); horizontal striped bar: “authorized” window for flowering to avoid biotic constraints such as panicle rot; solid line with open symbols: simulated mean flowering date. Arrows indicate the potential periods of sowing, corresponding to the cases where flowering falls into the authorized window.

Taking in account better knowledge on varietales types, resulting from the experimental studies and farms survey tendencies in different agro-ecological zone we will adapt this methodology over

West

Africa.

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